Synchronization Risk and Price Stickiness: Theory and Evidence*

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Abstract

Using online consumer review data, we find that when customers observe a firm charging a lower price than they previously paid for the same item, they feel antagonized and give the firm low ratings, leading to reputation costs for the firm. In particular, the firm's reputation costs are higher if it adjusts its price more quickly than other firms. Based on the empirical findings, we build a model to characterize the optimal timing for firms to adjust their prices, providing a microfoundation for price stickiness. In an environment with information frictions about how an aggregate shock affects the economy, individual firms face uncertainty about when their peers will adjust prices. This synchronization risk leads all individual firms to rationally choose to postpone price changes. Our model predicts both synchronized and unsynchronized price adjustments, depending on the degree of information frictions. The model provides a number of other predictions, which are consistent with the evidence documented in the literature.

Keywords: Price Stickiness, Synchronization Risk, Reputation Cost, E-commerce

JEL classification: D12, D83, E12, E39

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1 Introduction

"It seems essential, therefore, to gain a better understanding of precisely what firms mean when they say that they hesitate to adjust prices for fear of antagonizing customers."

—— *Blinder et al. (1998)*

Price stickiness is a foundational assumption of New Keynesian economics. Among the explanations for why prices are sticky, a leading one is that firms are reluctant to antagonize their customers. Blinder et al. (1998) conduct a survey of firms to assess the validity of various theories on sticky prices proposed by economists. Although the authors do not directly ask whether price changes are disliked by customers, a majority of respondents mention that frequent price changes would "antagonize" or "cause difficulties" with their customers (p. 308). Subsequent surveys conducted in Canada (Amirault et al., 2006) and European countries (Apel et al., 2005; Fabiani et al., 2005; Alvarez et al., 2006) report similar findings. Eyster et al. (2021), summarizing 14 surveys covering more than 12,000 firms, find that customer antagonism or price fairness concerns appeal to firms more than any other theory, with a median rank of 1 and a mean rank of 1.9.[1]

Despite survey evidence from the firm side showing firms' concerns about customer antagonism, there is limited direct empirical evidence from the consumer side supporting the existence of customer antagonism. A study by Anderson and Simester (2010) is one of the few studies in this direction. The authors examine how customers react when they discover that a product they purchased is being sold at a lower price by the same retailer. They find that customers respond by making fewer future purchases from the firm, especially for the firm's most valuable customers. However, Anderson and Simester's (2010) study still does not provide direct evidence that customers are antagonized by price changes. Moreover, since price adjustments are often a response to aggregate economic shocks, there is still a lack of empirical evidence on how a systemic shock to all firms (e.g., monetary shock, systemic production cost shock, aggregate TFP shock) affects the dynamic patterns of firms' price adjustments and customer antagonism.[2]

In this paper, we utilize online consumer reviews to analyze the impacts of downward price adjustments. Specifically, we investigate price reduction cycles in which all firms adjust their prices downward. We find that when customers observe a firm charging a lower price than they previously paid for the same item, they feel antagonized and tend to give the firm low ratings, creating a reputation cost for the firm. However, the reputation cost is lower if more of the firm's peers have already adjusted their prices before the firm.

[1] Customers' antagonism about price changes usually comes from the feeling that prices are unfair (Xia et al., 2004).

[2] Anderson and Simester (2010) did not directly inquire whether customers felt antagonized by price changes, and they focused on individual firms' random price discounts, not a systemic shock to all firms.

Our data is collected from one of China's largest e-commerce platforms, Jingdong. After purchasing an item from an online store, customers can give ratings and leave reviews on the store's website, which are publicly observable. By reading these online reviews, we can identify whether or not customers are antagonized by price changes. To control for product quality and to trace price cycles, we focus on a specific type of product, memory modules. We have three main findings. First, after a systemic shock, stores reduce their prices sequentially. Second, customers become antagonistic and give a store low ratings when they observe the store charging a lower price than they previously paid for the same item. Third, if a store adjusts its prices later than other stores, the degree of customer antagonism is reduced. That is, the more stores that have adjusted their prices, the lower the reputation cost of price adjustment.

Based on the empirical findings, we develop a model to characterize the optimal timing for firms to adjust their prices, providing a microfoundation for price stickiness. Our model shows that due to synchronization risk — individual firms faces uncertainty about how many of their peers have adjusted prices, all firms may rationally choose to postpone price changes in equilbiurm. Our model predicts both synchronized and unsynchronized price adjustments, and gives a number of other predictions that are consistent with the evidence documented in the literature.

In our model setting, when an aggregate shock (such as a monetary shock, systemic production cost shock, or aggregate TFP shock) hits the economy, firms are affected in a non-simultaneous manner or perhaps firms become aware of the occurrence of the shock sequentially. This non-simultaneous impact of the aggregate shock on firms is captured through an asynchronous-awareness setting following Abreu and Brunnermeier (2003). Namely, the shock occurs at an unobservable time, after which firms sequentially receive information that a shock has occurred and decide when to adjust prices. In other words, each firm is unaware of its position in the queue, not knowing how many other firms have received information before it.[3] Moreover, firms in our model incur reputation costs when adjusting prices, with lower costs incurred if more firms have made adjustments prior. Specifically, we assume that if the number of firms that have adjusted prices exceeds a certain threshold, there is no reputation cost for firms adjusting prices later. Therefore, our model reflects a coordination feature in price adjustment.

The equilibrium is characterized by the optimal timing of firms to adjust prices — the waiting time between receiving information and adjusting price. In a symmetric equilibrium, all firms use the same (symmetric) strategy of a waiting period after receiving information. In choosing the optimal timing of price change, a firm faces the following tradeoff. On the one hand, increasing the waiting time means that more other firms will adjust their prices before the firm and thus the firm's expected reputation cost due to its price change will be lower. On the other hand, postponing the

[3] Unlike in Mankiw and Reis (2002), where information also spreads sequentially among firms, a key distinction in our model is that a firm does not know how many other firms have received information before it.

price adjustment means that the firm has to sacrifice the higher profit flow since the price it sticks to deviates from the desired price ex post the economic shock. This tradeoff gives a unique optimal waiting time for firms.

Our model has a number of implications. First, our model predicts both synchronized and unsynchronized price adjustments, depending on the degree of information frictions. While the equilibrium under information friction is unique, there exists a continuum of self-fulfilling equilibria without information friction. Specifically, in the absence of information frictions, all firms realize the need to adjust prices simultaneously. If a firm believes that other firms will adjust prices at a certain time, it will optimally adjust prices at the same time, resulting in a self-fulfilling equilibrium. Therefore, our model accounts for both synchronized price changes (in the absence of information friction) and unsynchronized price changes (in the presence of information friction), aligning with the empirical evidence reported by Bils and Klenow (2004) and Nakamura and Steinsson (2008).

Second, our model has an implication for the relationship between firm market power and price stickiness. Our model predicts that firms with higher market power would delay their price adjustment for longer. In fact, for a firm with greater market power, the percentage of profit loss incurred by not adjusting its price to the desired level is smaller. Therefore, in the tradeoff between a higher profit flow and a higher potential reputation cost, it weighs the reputation cost more heavily, which means that it has a higher incentive to delay the price adjustment. This implication is consistent with several empirical findings (e.g., Borenstein and Shepard, 2002; Deltas, 2008; Höynck et al., 2023).

The third implication is regarding how the size of the shock affects price stickiness. Our model suggests that large shocks prompt firms to adjust prices more quickly. Intuitively, the larger the shock size, the more costly it is for firms to delay price adjustments. This implication is consistent with numerous empirical findings (e.g., Cavallo et al., 2023; Karadi and Reiff, 2019; Alvarez and Neumeyer, 2020; Alvarez et al., 2017; Bonadio et al., 2020; Auer et al., 2021). Our model also has other implications, namely how price stickiness is affected by the size of reputation costs, the persistence of reputation costs, and the speed of information spreading.

Related Literature

Empirically, our paper examines the role of customer antagonism induced by price adjustments. Hall and Hitch (1939) were among the pioneers in identifying that firms believed frequent price changes could alienate customers. More recently, Blinder et al. (1998) investigated the validity of various sticky price theories as perceived by firms, finding that a significant majority of respondents indicated that frequent price adjustments would antagonize their clientele. This sentiment was further corroborated by subsequent surveys (Amirault et al., 2006; Hall et al., 1997; Apel et al.,

2005; Fabiani et al., 2005).

Our empirical work is most closely related to Anderson and Simester (2010), both investigating the effect of downward price adjustments on customer antagonism.[4] Unlike the aforementioned survey evidence, Anderson and Simester (2010) provide empirical evidence that many customers stop purchasing if they observe a firm charging a lower price than they previously paid for the same item. Our empirical work complements Anderson and Simester (2010) in two ways. First, while Anderson and Simester (2010) do not provide direct evidence that customers are antagonized, our paper does so by utilizing customers' online reviews. Second, while Anderson and Simester (2010) focus on individual firms' random discounts, we examine a systematic shock affecting all firms and find that firms decrease their prices sequentially. More importantly, we show that customers are less antagonized and that reputation costs are lower when a firm adjusts its price later than others. This suggests that firms may have an incentive to delay price adjustments, a crucial feature of our theoretical model.

Our empirical work is also related to the growing literature that uses online scraped data to study price stickiness (Levy et al., 2011; Cavallo, 2017; Gorodnichenko and Talavera, 2017; Gorodnichenko et al., 2018; Cavallo, 2018). As a complement to these papers, we document reputation cost of price adjustment via customers' online reviews. More importantly, our paper investigates a systematic cost shock and finds that earlier price change is associated with higher reputation costs. Due to the limitation of our data, we cannot conduct a direct empirical analysis of how reputation cost affects firms' pricing. However, by using online data, many researchers have documented the significant influence of reputation concern or fairness perceptions on firms' pricing strategies (Li and Jain, 2016; Anbarci and Feltovich, 2018; Luca and Reshef, 2021; Carnehl et al., 2024).

Our paper provides empirical support for the theoretical work on customer antagonism and price stickiness. In Rotemberg (1982, 2005, 2011), the assumption that price adjustments will induce customers' antagonism is the driving force behind sticky prices. In Nakamura and Steinsson (2011), price rigidity works as a partial commitment device, which enables sellers to commit not to exploit customers' preferences to repeatedly purchase from the same seller. Another related literature is price fairness, this is because customers' anger about price changes usually comes from the feeling that prices are unfair (Xia et al., 2004). Eyster et al.(2021) embedded the price fairness concern in a New Keynesian model to study the effect of monetary policy. Fairness has also received attention from many different topics, such as labor market (Akerlof, 1982; Akerlof and Yellen, 1990), game theory (Rabin, 1993; Fehr and Schmidt, 1999; Charness and Rabin, 2002), contract theory (Fehr et al., 2007), etc.

Theoretically, the information friction in our model follows the asynchronous awareness frame-

[4] We did not conduct empirical analyses on customers' response to upward price adjustment. This is because some antagonized customers do not purchase from high-price shops and therefore cannot give online reviews to those firms.

work in the seminar work of Abreu and Brunnermeier (2002, 2003) (see also the following-up work of He and Manela, 2016; Liu et al., 2024). While our paper utilizes the asynchronous awareness to characterize information friction, AB's model is not directly applicable to our research question. Specifically, the benefit-cost tradeoff in our model operates in the opposite direction compared to that in AB's framework. Nonetheless, through a reasonable model setting, we demonstrate that asynchronous awareness can effectively address our research question. Furthermore, this framework has the potential to be extended to a variety of research questions that share a similar benefit-cost tradeoff structure as our model. In this regard, our work contributes to showcasing the broader applicability of asynchronous awareness as a versatile analytical tool. We will elaborate on this point in the main text of our model.

Among the vast literature on the micro-foundations of sticky prices, our paper is closely related to the seminal sticky information paper of Mankiw and Reis (2002). But different from Mankiw and Reis (2002), firms' asynchronous awareness in our model means they need to find the optimal timing of price adjustments, with the result of a delay in price adjustments. In this way, our paper is also related to papers on limited attention and imperfect information in which price rigidity reflects firms' optimal price-setting strategies (Golosov and Lucas Jr, 2007; Maćkowiak and Wiederholt, 2009; Matějka, 2016; Bordalo et al., 2020; L'Huillier, 2020). Since our model characterizes the interaction between firms' price adjustments, our paper is broadly related to macroeconomic studies examining the interactions between firms' price-setting decisions in (Caplin and Leahy, 1997; Athey et al., 2004; Nakamura and Steinsson, 2010; Klenow and Willis, 2016; Mongey, 2021; Wang and Werning, 2022; Alvarez et al., 2023; Auclert et al., 2024; Baqaee et al., 2024). Yet, the asynchronous awareness setting and the implications for the optimal timing of price adjustments distinguish our paper from, and complement, the aforementioned works.

Our paper's empirical and theoretical work reflects a strategic relationship among firms in price adjustments. Specifically, if more other firms have already adjusted prices, the reputation cost of price change for a firm will be lower. Thus, our work is related to the sticky price papers that emphasize the coordination feature among firms. In the Ball and Romer (1991) seminal paper, the source of strategic complementarity is the demand externality under a CES setup of Dixit and Stiglitz (1977) and Blanchard and Kiyotaki (1987). Our model intentionally abstracts from the demand externality, and the source of complementarity instead comes from the nature of reputation costs. Different from Ball and Romer (1991), the unique equilibrium of our model under the friction of asynchronous reputation features both asynchronous and delayed price adjustments. In addition, the price adjustment cost in Ball and Romer (1991) is a menu cost that is unavoidable in any case. In contrast, the price adjustment cost in our paper is reputation-related, and if all firms, or a sufficient number of firms, choose to adjust prices, the reputation cost disappears. This feature comes from our empirical findings and highlights a special coordination mechanism.

Another related paper is by Iyer, Malenko, and Schoar (2017), who argue that when product quality is unobservable, sellers may signal superior quality by maintaining low prices during cost shocks. Therefore, the reputation concerns contribute to price stickiness. Our paper differs from theirs in two perspectives. From the empirical perspective, we focus on goods of uniform quality and examine dynamic price adjustment patterns, which are absent in their paper.[5] Specifically, we document sequential price adjustments over time and find that firms adjusting prices more slowly incur lower reputation costs. From the theoretical perspective, our model diverges by analyzing the optimal timing of price adjustments and emphasizing the coordination feature in price adjustments. Furthermore, our model generates additional implications for price stickiness that align with empirical evidence.

Our paper is organized as follows. Section 2 describes data collection and processing, the measurement of reputation cost and shows our empirical results. Based on our empirical findings, Section 3 builds a theoretical model of sticky prices and discusses some implications of the model. Section 4 concludes. Related proofs and additional results can be found in the appendix.

2 Price Reduction and Reputation Cost: Online Evidence

Leveraging a novel dataset of online consumer reviews from the Jingdong platform, we uncover two new findings that shed light on the mechanisms behind price adjustment and price stickiness.

Finding 1: When customers observe a firm charging a lower price than what they previously paid for the same item, they tend to give the firm low ratings, imposing a reputation cost on the firm.

Finding 2: Firms adjust their prices sequentially in response to systematic shocks. Notably, a firm that delays price adjustments relative to others incurs lower reputation costs.

2.1 Data Description

We collected data from online stores on the Jingdong platform, a leading B2C online retailer in China listed on the NASDAQ-100 and included in the Fortune Global 500. On Jingdong, customers who purchase items can provide ratings and write reviews within 60 days of purchase. This window allows customers to observe price changes after purchasing an item and before submitting their reviews. These online customer reviews (hereafter OCRs) provide valuable insights into how customers perceive price changes. Under a scoring system where the maximum is 5 stars, the Jingdong platform officially categorizes post-purchase customer evaluations into three distinct tiers: positive

[5] This also implies a distinct source of reputation concerns. In Iyer, Malenko, and Schoar (2017), reputation concerns arise from unobservable product quality, whereas in our paper, they stem from customer antagonism toward price changes.

reviews (greater than 4 stars), neutral reviews (2 to 3 stars), and negative reviews (1 star or below).

We focus on a single category of goods: memory modules. It includes daily prices and corresponding OCRs for selected memory modules sold across various stores on the Jingdong platform.

Why focus on memory modules? We selected memory modules for several reasons that align with our empirical research objectives. First, memory modules are actively traded in online markets, ensuring a robust dataset. Second, their product characteristics, such as generation (DDR4), operating frequency (2666M), and memory capacity (8G), allow for precise control over quality-related variables. Most importantly, memory modules exhibit distinct price cycles, enabling us to identify and compare firms that adjust prices quickly with those that adjust prices more slowly. This distinction is critical for analyzing customers' antagonism toward varying speeds of price adjustment. Moreover, this empirical finding is a key feature captured in our theoretical model, which generates important implications for understanding price stickiness.

Data collection was conducted using an automated Tcl/Python script, ensuring comprehensive and timely capture of relevant information. This process, which included prices (including discounts), customer reviews, and product details, was structured into three main steps:

Step 1 - Collection of Unique Identifiers: The first step involves retrieving the unique identifier associated with each product listed across various online retailers on the Jingdong platform. These identifiers are essential for accessing detailed product information. For example, the identifier 69343640241, as embedded in the HTML document, corresponds to the unique product URL: https://item.jd.com/69343640241.html.

Step 2 - Extraction of Product Details: Using the unique identifiers, the script navigates to each product's "commodity details page", where it collects relevant information such as prices, discounts, and key attributes. This step ensures comprehensive documentation of the product's price and features.

Step 3 - Compilation of Customer Reviews: The script then accesses the "customer reviews page" to gather updated non-positive reviews (ratings from one star to three stars). These reviews allow us to assess customer reactions, particularly whether they express dissatisfaction upon discovering that the prices of items they previously purchased have decreased.

The dataset spans from June 1, 2019, to March 23, 2021, encompassing data from 1,200 stores. It includes 7,860,466 customer reviews—16,446 of which are non-positive—and 472,646 daily price quotes, each specifying a date and price for an online store. To minimize biases from inactive or underperforming stores, we focused on shops with extended activity periods (price quotes spanning more than two weeks) and valid user interactions, excluding inactive or invalid websites.

Figure 1 illustrates the average logarithmic price dynamics across all memory module stores in our sample, with shaded areas indicating periods of price declines. Notably, a significant price drop

occurred from March to December 2020, coinciding with a major supply shock in China.[6]

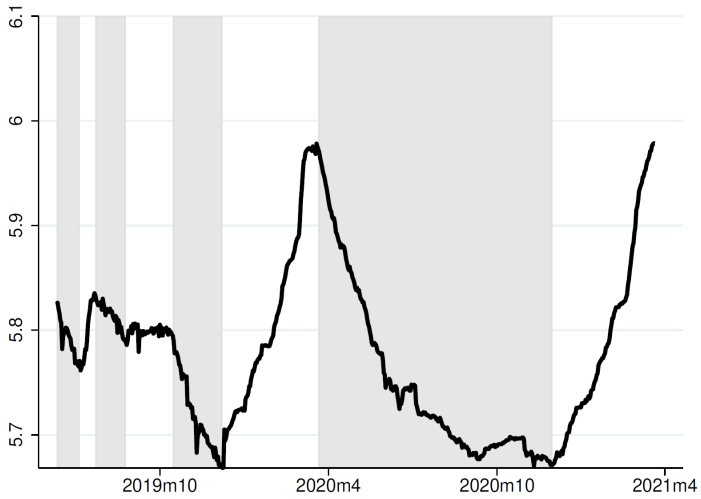


Figure 1: Dynamics of Average Logarithm Prices of Memory Modules

Note: Figure 1 shows the average logarithmic price dynamics for all memory module stores in our sample. The y-axis represents the logarithmic transformation of the pricing data. The shaded areas indicate periods of price decreases. The temporal scope of the data spans from June 1st, 2019, to March 23rd, 2021, and is sourced from the Jingdong platform.

Figure 2 illustrates the distribution of total review text counts across stores.

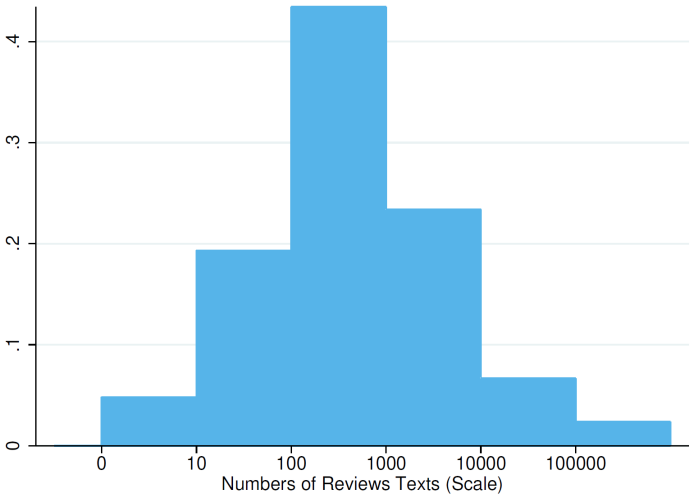


Figure 2: Distribution of numbers of review texts

Note: Figure 2 shows the distribution of review text counts across stores. The data covers the period from June 1st, 2019, to March 23rd, 2021, and is sourced from the Jingdong platform.

[6] According to industry reports from China Southwest Securities, the Chinese firm Changxi introduced a new mass-production technology for memory chips, competing with Micron's traditional technology, potentially contributing to the observed reduction in memory module prices.

2.2 Measurements

In the empirical analysis, we focus on customer antagonism caused by price reduction. We do not examine antagonism resulting from price increases, as consumers facing price hikes often forgo purchases, either by waiting or switching to lower-priced stores. Although such consumers may still experience antagonism, their decision to forgo purchases prevents them from leaving online reviews for the stores that caused their dissatisfaction. Consequently, identifying customer antagonism resulting from price increases is significantly more challenging.

2.2.1 Measuring reputation cost

We define the reputation cost for shop i in month t as the ratio of low-rating (non-positive-level) OCRs that mention "price reduction" in month t to the overall count of low-rating OCRs recorded within the same month.[7] Specifically,

$$RC_{it}^{reduce} = \frac{\#OCR_{L,it}^{reduce}}{\#OCR_{L,it}} \times 100\% \tag{1}$$

where RC_{it}^{reduce} denotes the monthly reputation cost associated with price reductions. The numerator $\#OCR_{L,it}^{reduce}$ denotes the count of low-rating OCRs associated with price reductions for shop i in month t, which are extracted from the OCRs textual data, providing a clear and direct measure of consumer dissatisfaction stemming from price reductions. The denominator $\#OCR_{L,it}$ denotes the total count of low-rating OCRs for shop i in month t, encompassing all instances of non-positive feedback. Therefore, RC_{it}^{reduce} provides an intuitive way to quantify the reputation cost associated with price reductions. Nonetheless, several important considerations require further explanation.

In our definition of reputation cost, the denominator $\#OCR_{L,it}$ is the total count of low-rating OCRs. We focus on low-rating reviews for three practical reasons. First, the Jingdong platform defaults OCRs to the highest rating when consumers do not proactively submit reviews. This practice results in an overrepresentation of high-rating OCRs. By excluding high-rating OCRs from the denominator, we reduce bias caused by these default-generated ratings. Second, many customers provide high ratings immediately after purchase; if they later encounter a price reduction, they cannot revise their initial ratings, even if antagonized. Third, using low-rating OCRs as the denominator offers a methodological advantage: their smaller total count increases the variance of RC_{it}^{reduce}, making it more suitable for regression estimation.

To count the number of low-rating OCRs related to price reductions, we employ a textual analysis method using a set of keywords associated with "price reduction". These keywords span

[7] We use the ratio rather than the absolute number because ratios can help mitigate the impact of extreme values and makes different stores comparable. This approach is also consistent with common methods in textual analysis, such as word frequency techniques.

a spectrum from broad to narrow definitions. For example, the most relaxed criterion includes OCRs referencing either the act of price reduction, with terms like "price reduction" or "cheaper", or the condition of low prices, using phrases such as "low price level" or "cheap". In contrast, the strictest criterion focuses exclusively on OCRs that explicitly mention the act of price reduction. Our analysis yields consistent and robust results across these varying definitional thresholds.

We aggregate OCRs on a monthly basis rather than daily or weekly for two reasons. First, many stores do not receive a sufficient volume of OCRs at high frequencies, such as daily or weekly, which could compromise the robustness of the analysis. Second, OCRs are typically submitted within two weeks of purchase, leading to potential delays in submission. These delays can distort results if higher-frequency data are used. Aggregating OCRs monthly effectively addresses these challenges.

Concerns about the veracity of OCRs are valid, particularly given the possibility that some low-rating OCRs may be posted by malicious competitors, as highlighted by Mayzlin et al. (2014). However, the Jingdong platform mitigates this risk by allowing only verified buyers to leave reviews, making such behavior costly and less prevalent. To further ensure the integrity of our analysis, we adopt a cautious approach in our textual analysis. Specifically, we exclude OCRs flagged as suspicious, applying a reasonable threshold by filtering out reviews reported more than ten times.

2.2.2 Measuring sticky stores

In this part, we categorize firms into two groups: those that reduce prices quickly (non-sticky group) and those that reduce prices slowly (sticky group).

To differentiate between sticky and non-sticky stores, we first focus on a prolonged and systematic price reduction cycle in our dataset, which spans from March 23, 2020, to December 22, 2020 (see Figure 1). Following a significant negative price shock in March 2020, we observed that stores lowered their prices gradually (the average price decreases nearly 30%), albeit with varying degrees of stickiness. Since stores adjust prices at different speeds, by the end of the price decline cycle, the extent of price reductions varied across stores. For simplicity, we classify a store as sticky if it takes longer to achieve a 5% price reduction relative to its price in March 2020.[8]

By arranging the number of days it takes for all stores to reduce their prices by 5% in ascending order, we group the stores into quantiles, as presented in Table 1. According to the table, the fastest 20% of stores achieve a 5% price reduction within 6 days, whereas the subsequent 20% accomplish this within 6–15 days. The slowest 20% of stores complete a 5% price reduction after at least 74 days. An important implication of Table 1 is that firms adjust their prices sequentially rather than

[8]Some literature employs the frequency of price adjustments, as seen in Gorodnichenko and Weber (2016), to measure stickiness in a broader context. Our approach here is a more direct measure of price stickiness. In Appendix C, we use more methods to distinguish sticky and non-sticky stores and our empirical findings still hold.

simultaneously, consistent with Finding 2 outlined at the beginning of this section.

Table 1: Number of Days to Complete a 5% Price Reduction

Quantiles	Number of Days
20%	6
40%	15
median	21
60%	32
80%	74

We categorize non-sticky stores as those with price adjustment periods below the median and sticky stores as those above the median. To mitigate the influence of extreme values, we apply winsorization to the top and bottom 2% of stores. In our sample, both sticky and non-sticky groups contain 467 stores.

Figure 3 illustrates the price declince patterns for both sticky and non-sticky stores. We first compute the average prices of sticky and non-sticky stores respectively, then we compute the price decline rate. The blue line represents the price reduction rate of the sticky group, while the red line represents the price reduction rate of the non-sticky group. It is clear that the sticky stores reduce their prices more slowly than the non-sticky stores.



Figure 3: Price Decline Patterns of Sticky and Non-sticky Stores

Note: Figure 3 displays the price dynamics of sticky and non-sticky stores. The starting point is March 23, 2020, when the downward price shock occurred.

2.3 Empirical Findings

We now show the empirical findings. First, we demonstrate that the reputation cost associated with price reduction exists. Second, we demonstrate that firms reduce prices more quickly incur higher reputation costs.

To test whether customers are antagonized by price reductions, it is imperative to differentiate periods of price reductions from other periods. As is shown in Figure 1, the most prolonged and systematic period of price decrease is identified as March 23, 2020, to December 22, 2020. Therefore, we employ a binary variable dec_time_t to demarcate this period of price decline.[9] The subsequent model is then applied:

$$RC_{it}^{reduce} = \alpha_i + \beta \text{dec_time}_t + \text{Controls}_{it} + \epsilon_{it} \tag{2}$$

where RC_{it}^{reduce} is the reputation cost associated with price reductions. dec_time_t is the binary indicator for the price reduction period, and α_i denotes the individual fixed effect. We incorporate time-varying store-level controls and store-level fixed effect.[10] The coefficient β reflects the difference in reputation costs between periods of price reductions and other periods. Table 2 shows the main results.

Table 2: Existence of Reputation Costs

	(1)	(2)	(3)	(4)
Dec-time	4.51***	4.66***	4.81***	5.10***
	(0.495)	(0.510)	(0.496)	(0.518)
Store FE	N	N	Y	Y
Controls	N	Y	N	Y
Cluster	N	Y	Y	Y
Observations	5754	5754	5599	5599
R^2	0.014	0.016	0.13	0.13

Note: This table reports the results of regressing reputation costs on the price decrease dummy variable. Column (1) reports a simple OLS regression without fixed effects. Column (2) includes control variables and firm-level clustered standard errors. Column (3) employs a basic fixed effects model with clustering but excludes control variables. Column (4) presents results from the standard fixed effects model. Statistical significance levels of 1 percent, 5 percent, and 10 percent are indicated by ***, ** and *, respectively.

According to Table 2, price reductions lead to a statistically significant increase in reputation costs, with an observed rise of 4%-5% during periods of systematic price declines. This result

[9] Our empirical results remain the same if we use dec_time_t to denote all price-decline periods in Figure 1.

[10] In our regression, we incorporate several control variables: the response ratio (RespRat), which indicates the proportion of store responses to OCRs; the presence of an "advertising push" label (AdvPush); whether the store is a JD Logistics partner (JDLogP); and the availability of visual reviews such as images or short videos (VisRev).

remains consistent across different control variables. Additional robustness checks are presented in Appendix C.

Now we conduct a regression analysis related to Finding 2. We estimate the following model.

$$RC_{it}^{reduce} = \lambda_t + \gamma \text{non_sticky}_i + \text{Controls}_{it} + \epsilon_{it} \tag{3}$$

The variable non_sticky_i is a dummy variable equal to one if a store is non-sticky, and λ_t represents the time fixed effect. We incorporate time-varying store-level controls and time fixed effect. Table 3 presents the results.

According to Table 3, stores that reduce prices more quickly incur significantly higher reputation costs, nearly 4% under various regression controls. In Appendix C, we provide additional robustness checks which are consistent with our findings here.

Table 3: Price Reduction Speed and Reputation Cost

	(1)	(2)	(3)	(4)
non-sticky	3.80***	3.94***	3.65***	3.74***
	(1.12)	(1.13)	(1.09)	(1.10)
Time FE	N	N	Y	Y
Controls	N	Y	N	Y
Cluster	N	Y	Y	Y
Observations	1598	1598	1589	1589
R^2	0.007	0.012	0.13	0.14

Note: This table reports the results of regressing reputation costs on the non-sticky dummy variable. Column (1) presents a simple OLS regression without fixed effects; Column (2) incorporates control variables and firm-level clustered standard errors; Column (3) uses a basic fixed effects model with clustering but excludes control variables; and Column (4) reports results from the standard fixed effects model. Statistical significance levels of 1 percent, 5 percent, and 10 percent are indicated by ***, ** and *, respectively.

3 A Model of Reputation Cost and Price Stickiness

Motivated by the evidence on consumer antagonism and reputation costs, in this section we build a model to provide a micro foundation for price stickiness. Specifically, our model incorporates information frictions in the spirit of Abreu and Brunnermeier (2003) and reputation costs of price changes. Individual firms choose their optimal timing to adjust prices by considering the tradeoff between profit flows and reputation costs. We show that in equilibrium individual firms may deliberately postpone their price adjustment, leading to price stickiness. The comparative statics of the model yields a number of empirical predictions.

3.1 Model Setting

We build a partial equilibrium model. Time is continuous and starts from $t = 0$. The risk-free net interest rate is assumed to be r. All agents are risk-neutral.

Firms. As in the endogenous growth model setting of Romer (1990), a representative final goods producer uses a continuum of intermediate goods, indexed by $i \in [0, 1]$, as inputs in production. The production function of the representative final goods producer is

$$Y(t) = \frac{1}{1-\alpha} \int_0^1 y_i(t)^{1-\alpha} di, \tag{4}$$

where $y_i(t)$ is the input of intermediate goods i and $\alpha \in (0, 1)$ measures the monopoly power of intermediate goods firms (i.e., $\varepsilon_\alpha \equiv 1/\alpha$ is the elasticity of substitution between intermediate goods). The profit optimization problem of the final goods producer, $\max_{\{y_i(t)\}} \frac{1}{1-\alpha} \int_0^1 y_i(t)^{1-\alpha} di - \int_0^1 p_i(t) y_i(t) di$, generates the demand function for intermediate goods:

$$y_i(t) = p_i(t)^{-1/\alpha}, \tag{5}$$

where $p_i(t)$ is the price of intermediate goods i and the final goods price is normalized as 1. It is important to note that unlike Ball and Romer (1991), the production function (4) in our model is not a Dixit-Stiglitz CES production, so there is no aggregate demand externality between intermediate goods. In fact, in (5), the demand for intermediate goods i does not depend on the aggregate demand Y.

We assume that all intermediate goods firms have a constant-returns-to-scale technology with productivity z or equivalently their unit cost is $c \equiv 1/z$. An intermediate goods firm sets its price to maximize profit

$$\max_{p_i(t)} p_i(t) y_i(t) - c y_i(t).$$

Using the demand function (5), the first-order condition over $p_i(t)$ gives firm i's optimal price

$$p_i(t) = \frac{c}{1-\alpha} \tag{6}$$

which also implies that firm i's optimal output is $y_i(t) = \left(\frac{c}{1-\alpha}\right)^{-\frac{1}{\alpha}}$ and its profit flow at time t is

$$\pi_i(t) = \alpha \left(\frac{c}{1-\alpha}\right)^{1-\frac{1}{\alpha}}. \tag{7}$$

Aggregate shock and information frictions. An aggregate shock strikes the economy at a random and unobservable time t_0. The shock can be a real shock on productivity or unit cost, or

a shock in the money supply that impacts nominal prices. It is common knowledge that t_0 follows an exponential distribution on the interval $[0, +\infty)$ with a cumulative distribution function (c.d.f.) $\Phi(t_0) = 1 - e^{-\lambda t_0}$ (the corresponding p.d.f. being $\phi(t_0) = \lambda e^{-\lambda t_0}$), where $\lambda > 0$ is a constant.

The aggregate shock may not affect firms simultaneously and homogeneously. In the spirit of Abreu and Brunnermeier (2003), we characterize the non-simultaneous impact of the aggregate shock on firms through the asynchronous awareness setting.[11] Specifically, we assume that after t_0, firms sequentially receive the information that the aggregate shock has happened. The information spreads among firms uniformly over time $[t_0, t_0 + \eta]$, where $\eta > 0$. We call the firms that have received information about the shock as informed firms, and the rest as uninformed firms. Therefore, the fraction of informed firms is $\frac{t-t_0}{\eta}$ by time $t \in [t_0, t_0 + \eta]$. Particularly, since the shock time t_0 is random and unobservable, an informed firm does not know its position in the queue (i.e., does not know how many other firms are informed before or after it). From now on, we use firm t_i to denote a firm that receives information at time $t_i \in [t_0, t_0 + \eta]$.

As we can see, similar to the sticky information setting of Mankiw and Reis (2002), our model assumes that firms receive information sequentially. However, the key difference from their model setting is that an informed firm in our model does not know how many of its peers have received information before it. As we will show, this difference in information frictions opens the door for delayed price adjustments for firms, and the endogenous optimal timing of price adjustment allows us to investigate how price stickiness depends on economic environments.

Suppose that firms' unit production cost changes from c to $c^{'}$ after the shock. If an informed firm chooses its optimal, new price $p_j(c') = \frac{c^{'}}{1-\alpha}$ according to (6), its profit flow would be

$$\pi_H \equiv \alpha \left(\frac{c^{'}}{1-\alpha} \right)^{1-\frac{1}{\alpha}}.$$

However, if it sticks to its original price $p_j(c) = \frac{c}{1-\alpha}$, its profit flow is

$$\pi_L \equiv \left(\frac{c}{1-\alpha} - c^{'} \right) \left(\frac{c}{1-\alpha} \right)^{-\frac{1}{\alpha}}.$$

Reputation cost of price adjustment. Our empirical study finds that a firm's reputation cost of price adjustment is lower if more other firms have adjusted prices. To capture this feature, we assume that a reputation cost is incurred only for the first $\kappa \in (0, 1)$ fraction of firms that adjust prices early.[12] For the remaining $1 - \kappa$ fraction of firms that adjust prices late, there is no

[11] The setting of asynchronous awareness captures both of the following situations. First, the aggregate shock affects all firms simultaneously starting at t_0, but they become aware of the occurrence of the shock sequentially ("information spreading"). Second, the shock affects firms sequentially and they are informed once they are affected ("impact spreading").

[12] More precisely, firms $i \in [0, \kappa)$ incur the reputation cost and firms $i \in [\kappa, 1]$ do not.

reputation cost.

Specifically, denoting by $RC_i(t)$ the reputation cost for firm i to adjust its price at time t, we assume

$$RC_i(t) = \begin{cases} \max\left(\varrho\left[1-(t-t_0)/\beta\right],0\right) & i \in \text{ the first } \kappa \text{ fraction of firms} \\ 0 & \text{otherwise} \end{cases} . \tag{8}$$

In the first line of (8), it is assumed that the reputation costs per se declines over time, which is reasonable. The rationale is the following. Over time, as more and more customers realize that a shock has occurred to firms, these customers understand that a price adjustment is necessary. Thus, over time, customers as a whole become more tolerant of price adjustments. Spefically, we assume that the information of the shock occurance t_0 spreads among customers uniformly over time $[t_0, t_0+\beta]$, where $\beta > 0$. So $1/\beta$ represents the diminishing speed of the reputation cost, while the parameter $\varrho > 0$ represents the magnitude of the reputation cost. Importantly, since t_0 is unobservable, a firm does not perfectly know the reputation cost incurred on its price adjustment.

To make our research question interesting, we make three assumptions on parameter values, listed at the beginning of the appendix.

Remark 1. While we adopt the information friction of asynchronous awareness following Abreu and Brunnermeier (2002, 2003, hereafter AB), their model framework is not directly applicable to our research question. In AB's models, when the bubble bursts, it becomes public information and thus t_0 is revealed to all arbitrageurs, including those who have not yet taken a short position at that time. And those arbitrageurs who have not yet taken a short position cannot take a short position after the bubble bursts. In contrast, in our model, when the event occurs that a κ fraction of firms have already adjusted their prices, this event does not become public information and thus t_0 is not revealed to firms, including those that have not yet adjusted their prices. And the remaining $1-\kappa$ fraction of firms still adjust prices sequentially after this event. This assumption is not only reasonable in our context, but also necessary to deliver our economic insight, which will be discussed in Remark 2.

3.2 Equilibrium

We are interested in a symmetric equilibrium, in which all firms use the same (symmetric) strategy of waiting period after receiving information. That is, each firm decides to wait for a time interval τ after receiving information before adjusting its price. Denote by $t_0+\zeta$ the point in time by which a κ fraction of firms have adjusted prices (which implies that a price adjustment will not incur reputation cost after time $t_0+\zeta$). The equilibrium is characterized by the pair (τ^*, ζ), where τ^* is the optimal choice of τ for individual firms in equilibrium.

Solving ζ as a function of τ^*. Under a symmetric delay strategy τ, the fraction of firms

that have adjusted price by time t is given by $N(t) = \frac{t-(t_0+\tau)}{\eta}$ for $t \in [t_0+\tau, t_0+\tau+\eta]$. By definition of ζ, at time $t_0+\zeta$, the fraction of firms that have adjusted price equals the threshold value κ. Hence, $N(t_0+\zeta) = \kappa$ gives

$$\zeta = \tau^* + \kappa\eta. \tag{9}$$

The posterior belief of t_0. Since the shock time t_0 is unobservable, a firm receives information at time t_i only knows that $t_0 \in [t_i - \eta, t_i]$.[13] Hence, the posterior p.d.f of t_0 from the perspective of firm t_i is given by

$$\phi(t_0 \mid t_i) = \frac{\phi(t_0) f(t_i \mid t_0)}{\int_{t_i-\eta}^{t_i} \phi(s) f(t_i \mid s) ds} = \frac{\lambda e^{\lambda(t_i - t_0)}}{e^{\lambda\eta} - 1}. \tag{10}$$

Optimal waiting strategy of individual firms. In solving the optimal waiting strategy, firm t_i takes other firms' choice τ^* and thus the equilibrium ζ as given. Denoting by τ_i firm t_i's waiting time before adjusting its price, firm t_i's optimal choice on τ_i is given by

$$\tau_i^* = \arg\max_{\tau_i} \left\{ \begin{array}{l} \int_{t_i+\tau_i-\zeta}^{t_i} \underbrace{\phi(t_0|t_i)}_{\text{density function}} \underbrace{\left[\int_{t_i}^{t_i+\tau_i} e^{-r(t-t_i)} \pi_L dt + \int_{t_i+\tau_i}^{+\infty} e^{-r(t-t_i)} \pi_H dt - e^{-r\tau_i} RC(t_i+\tau_i) \right]}_{\text{payoff if reputation cost occurs}} dt_0 \\ + \int_{t_i-\eta}^{t_i+\tau_i-\zeta} \underbrace{\phi(t_0 \mid t_i)}_{\text{density function}} \underbrace{\left[\int_{t_i}^{t_i+\tau_i} e^{-r(t-t_i)} \pi_L dt + \int_{t_i+\tau_i}^{+\infty} e^{-r(t-t_i)} \pi_H dt \right]}_{\text{payoff without reputation cost}} dt_0 \end{array} \right\}. \tag{11}$$

We explain the objective function in the program (11), with an illustration in Figure 1. In the objective function, firm t_i maximizes the present value at t_i by discounting all future payoffs. The individual firm which receives information at t_i only knows $t_0 \in [t_i - \eta, t_i]$.[14] Given its waiting strategy τ_i, there are two possibilities. The first possibility is $t_i + \tau_i < t_0 + \zeta$ (equivalently $t_0 \in (t_i + \tau_i - \zeta, t_i]$), that is, firm t_i belongs to the first κ^- fraction of firms that adjust prices and thus it pays the reputation cost. In this case, its expected payoff is given by the first term on the right-hand side (RHS) of (11). The second possibility is $t_i + \tau_i \geq t_0 + \zeta$ (equivalently $t_0 \in [t_i - \eta, t_i + \tau_i - \zeta]$), that is, firm t_i belongs to the $1 - \kappa$ fraction of firms that adjust price late and thus it does not incur the reputation cost. In this case, its expected payoff is given by the second term on the RHS of (11).[15]

[13] We consider only the case $t_0 \geq \eta$. The model is robust to the case $t_0 < \eta$ (see the proof in Abreu and Brunnermeier (2003) and Liu et al. (2024)).

[14] This is different from the case in Abreu and Brunnermeier (2002, 2003), where once the bubble bursts, everyone is informed of this event, so individual arbitrageurs, if they have not taken a short position, have an additional piece of information $t_i < t_0 + \zeta$, which gives $t_0 \in (t_i - \zeta, t_i]$. In our model, even if the time $t_0 + \zeta$ has arrived, individual firms do not know it, so $t_0 \in [t_i - \eta, t_i]$.

[15] From Figure 1, we can see an important difference from the setting of Brunnermeier (2002, 2003), where there are no such "late" agents who can take their action *after* time $t_0 + \zeta$. That is, in their papers, late agents $t_i + \tau_i \geq t_0 + \zeta$ are *passively* out of the game at $t_0 + \zeta$.

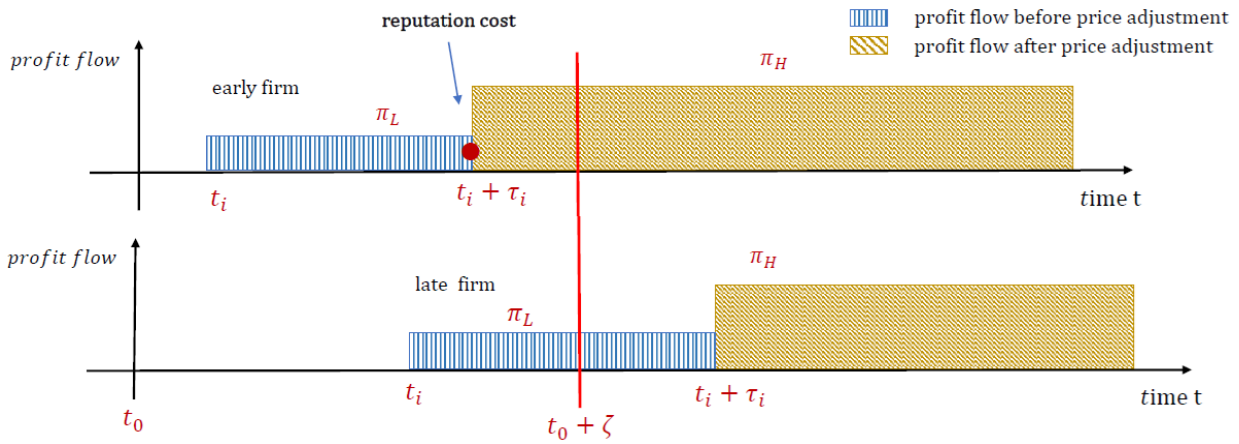


Figure 4: Payoff for firm t_i in two cases

Note: Firm t_i with waiting strategy τ_i, not knowing its position in the queue, understands that it must be one of the two cases. Case 1 is that it is an "early" firm with $t_i+\tau_i < t_0+\zeta$ (equivalently $t_0 \in (t_i+\tau_i-\zeta, t_i]$). In this case, it obtains profit flow π_L during $t \in [t_i, t_i+\tau_i]$ and profit flow π_H during $t \in (t_i+\tau_i, \infty)$, and incurs reputation cost $RC(t_i+\tau_i)$ at $t = t_i+\tau_i$. Case 2 is that it is a "late" firm with $t_i+\tau_i \geq t_0+\zeta$ (equivalently $t_0 \in [t_i-\eta, t_i+\tau_i-\zeta]$). In this case, it obtains profit flow π_L during $t \in [t_i, t_i+\tau_i]$ and profit flow π_H during $t \in (t_i+\tau_i, \infty)$, but it does not incur any reputation cost.

Denoting by $\Psi(\tau_i)$ the objective function in program (11), the first-order condition $\frac{d\Psi(\tau_i)}{d\tau_i}\Big|_{\tau_i=\tau_i^*} = 0$ implies

$$\underbrace{\phi(t_i+\tau_i^*-\zeta|t_i)\cdot\varrho\,(1-\zeta/\beta)}_{\text{benefit of switching from paying RC to not}} + \underbrace{\int_{t_i+\tau_i^*-\zeta}^{t_i}\phi(t_0|t_i)\cdot\{r\varrho\,[1-(t_i+\tau_i^*-t_0)/\beta]+\varrho/\beta\}\,dt_0}_{\text{benefit due to decreasing RC over time and time discount vlaue}}$$
$$-\underbrace{1\cdot(\pi_H-\pi_L)}_{\text{cost in profit flow}} = 0. \tag{12}$$

The economic intuition behind (12) is the following. First, when delaying the price adjustment by increasing τ_i a bit, the firm i may benefit drastically, by switching from paying the reputation cost to not paying it. This happens only when firm i's price adjustment time $t_i+\tau_i$ is instantly ahead of the point in time $t_0+\zeta$. That is, the probability density of this event is $\phi(t_i+\tau_i = t_0+\zeta \mid t_i)$ or equivalently $\phi(t_i+\tau_i-\zeta \mid t_i)$. When this happens, the saved reputation cost is $\varrho\,(1-\zeta/\beta)$. Second, conditional on firm t_i paying the reputation cost (i.e., firm t_i belonging to the first κ fraction of firms adjusting prices), delaying price adjustment by increasing τ_i also has benefit, because the reputation cost per se decreases over time (see (8)) and also the present discount value of the reputation cost goes down (by noting that the time discount factor is $e^{-r\tau_i}$). Third, of course, delaying the price adjustment by increasing τ_i entails a deviation from the optimal pricing strategy

and thus yields the loss in profit flow, $\pi_H - \pi_L$, with *probability 1*.[16]

Applying (10) to equation (12), we can verify that both the first and second terms on the LHS of equation (12) are decreasing in τ_i^*. Hence, the LHS of the first-order condition is decreasing in τ_i^* and thus the first-order condition (12) is sufficient for the maximization problem of (11). Denoting by $\Gamma(\tau_i)$ the sum of the first two terms on the LHS of (12), Figure 2 illustates the tradeoff in (12).

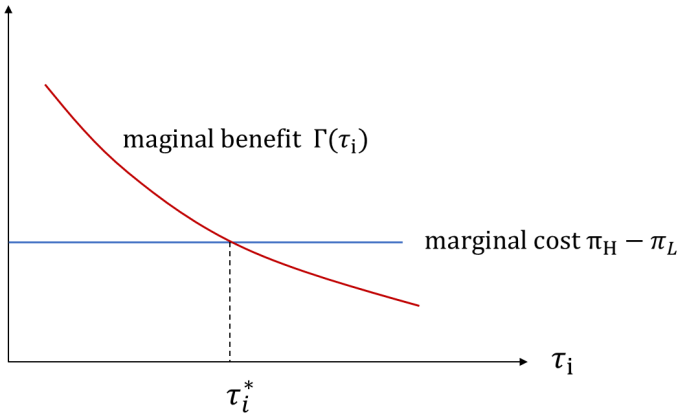


Figure 5: The tradeoff for individual firm t_i in choosing optimal waiting time

Lemma 1 *Given its rational expectation about ζ, individual firm i chooses its optimal delay time τ_i^*, given in (12).*

Solving the equilibrium. The equilibrium is a fixed-point problem between τ^* and ζ. Given τ^*, ζ is determined by (9). Given ζ, the optimal waiting strategy τ_i^* for firm t_i is determined by (11), and by symmetric equilibrium

$$\tau^* = \tau_i^*. \tag{13}$$

Substituting (9) and (13) into (12), the single equation that characterizes the equilibrium is

$$\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\varrho\left[1-\left(\tau^*+\kappa\eta\right)/\beta\right]+\int_0^{\kappa\eta}\frac{\lambda e^{\lambda x}}{e^{\lambda\eta}-1}\cdot\left\{r\varrho\left[1-\left(x+\tau^*\right)/\beta\right]+\varrho/\beta\right\}dx-\left(\pi_H-\pi_L\right)=0. \tag{14}$$

It is easy to check that the LHS of (14) is monotonically decreasing in τ^*, so there is a unique solution with respect to τ^*. When $r \to 0$, equation (14) is simplified as

$$\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\varrho\left[1-\left(\tau^*+\kappa\eta\right)/\beta\right]+\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\left(\varrho/\beta\right)-\left(\pi_H-\pi_L\right)=0, \tag{15}$$

which clearly admits a unique solution of τ^*. Under parameter assumptions 1 and 2 (listed at the beginning of the appendix), Proposition 1 follows.

[16] Probability 1 is due to the fact that both an "early" and a "late" firm incur the loss in profit flow when delaying price adjustment. In contrast, in AB's models, this probability is $\Pr\left(t_i+\tau_i<t_0+\zeta|t_i\right)$ — the probability that arbitrageur t_i is an "early" arbitrageur who shorts before the bubble bursts.

Proposition 1 *The equilibrium waiting time τ^* for firms is given by the system of equations (9), (12) and (13). There exists a unique equilibrium, in which $\tau^* > 0$ and firms adjust their prices sequentially in the time window $[t_0 + \tau^*, t_0 + \tau^* + \eta]$.*

Proposition 1 shows *unsynchronized* and *delayed* price adjustments for firms. The delay arises because individual firms face synchronization risk: each individual firm faces uncertainty about how many of its peers have adjusted prices. This synchronization risk leads all individual firms to rationally choose to postpone price changes in equilibrium. Proposition 1 is important because it implies that even if firms have received information and realized the need to adjust prices, they may still deliberately postpone price changes. This differs from the sticky information model of Mankiw and Reis (2002), where firms adjust prices immediately upon receiving information.

The result of unsynchronized and delayed responses in the unique equilibrium in Proposition 1 depends critically on i) the coordination motive in price adjustment among firms and ii) information frictions in the form of asynchronous awareness among firms. In fact, Proposition 1 holds only if $\beta > 0$ is sufficiently high (see the parameter assumptions listed at the beginning of the Appendix) and $\eta > 0$. Recall that β measures the window of information spreading among customers while η measures the window of information spreading among firms. We now examine what happens when one of the parameter assumptions is relaxed.

Proposition 2 *If $\eta = 0$ (and $\beta > 0$), there exists a continuum of equilibrium in which all firms adjust prices* ***simultaneously*** *at some $t_0 + \tau^*$, where τ^* is any value belonging to $[0, \beta]$.*

When $\eta = 0$ and $\beta > 0$, it means that there is no asynchronous awareness among firms, but the coordination motive in price adjustment among firms still exists. In this case, the time of the shock, t_0, becomes common knowledge among firms, under which coordination in price adjustments among firms can lead to multiple self-fulfilling equilibria. In fact, any $\tau^* \in [0, \beta]$ forms an equilibrium. In contrast, in Proposition 1, information frictions in the form of asynchronous information make the time of the shock t_0 never common knowledge (Abreu and Brunnermeier (2002, 2003)), leading to a unique equilibrium and a delayed response in equilibrium.[17] It is worth noting that in Proposition 2 the upper bound of τ^* increases with β. The intuition is the following. An increase in β means that the reputation cost decreases more slowly over time. As a result, given the waiting choice $\tau^*$of other firms, a firm that opts to adjust its price earlier incurs a higher reputation cost. This reduces the firm's incentive to adjust its price earlier. Consequently, the upper bound of τ^* that can be sustained in equilibrium increases with β.

[17] This is in the same spirit as the static global games model of Carlsson and van Damme (1993) and Morris and Shin (1998), where the introduction of a tiny degree of heterogeneous noise in agents' information signals leads to a unique equilibrium.

Our model hence predicts both synchronized and unsynchronized price adjustments, depending on whether information frictions exist (Propositions 1 and 2). As documented by Bils and Klenow (2004) and Nakamura and Steinsson (2008), an important feature of price adjustment is that there exist both synchronized and unsynchronized price adjustments.[18] It is challenging for the traditional microfoundation of sticky prices, such as menu cost, to rationalize the synchronized and unsynchronized patterns. Our model provides an explanation. On the one hand, when there is no heterogeneous information (namely $\eta = 0$), if a firm believes its peers will adjust prices at time $t_0 + \tau^*$, then adjusting price at $t_0 + \tau^*$ is the optimal strategy, and τ^* becomes a self-fulfilling equilibrium. This corresponds to synchronized sales where firms know other firms will adjust prices at a certain time. On the other hand, when heterogeneous information exists ($\eta > 0$), firms cannot form a common belief on the exact time when their peers will adjust prices. In this case, firms will adjust prices sequentially in equilibrium, corresponding to unsynchronized price adjustments.

Proposition 3 *If $\beta = 0$ (and $\eta > 0$), there exists a unique equilibrium in which $\tau^* = 0$ (that is, all firms adjust their prices **immediately** upon receiving information).*

When $\beta = 0$, there are no reputation costs associated with price adjustments, and thus no coordination motive among firms in price adjustment. In this case, firms would adjust their prices immediately upon becoming aware of the shock. However, because $\eta > 0$, firms still adjust prices sequentially. Corollary 1 examines the extreme case.

Corollary 1 *If $\eta = 0$ and $\beta = 0$, there exists a unique equilibrium in which $\tau^* = 0$ (that is, all firms adjust their prices **simultaneously** and **immediately** at t_0).*

When $\eta = 0$ and $\beta = 0$, it means that there is no asynchronous awareness among firms and no reputation costs associated with price adjustments. Consequently, the unique equilibrium is characterized by all firms adjusting their prices immediately and simultaneously at time t_0. Corollary 1 may help to explain some phenomena of synchronized price adjustments in reality, such as those observed during Black Friday or Cyber Monday sales. During these events, firms know that their peers will all adjust their prices. Meanwhile, customers expect that firms will lower prices and do not view such price adjustments negatively. As a result, firms respond to this mutual understanding by simultaneously lowering prices on these specific days.

Remark 2. The difference in our model setting compared to that of Abreu and Brunnermeier (2002, 2003) is not only reasonable for our research question but also essential to obtain our model result. In fact, if we use AB's original setting, our model does not work. The essence of AB's

[18] Examples of synchronized price changes include holiday sales and seasonal sales.

models (see Abreu and Brunnermeier (2002)) can be summarized by the first-order condition

$$-\underbrace{f\left(t_i+\tau_i=t_0+\zeta|t_i\right)\cdot\text{stock value}}_{\text{expected cost of waiting by increasing }\tau_i}+\underbrace{\Pr\left(t_i+\tau_i<t_0+\zeta|t_i\right)\cdot\text{flow value}}_{\text{expected benefit of waiting by increasing }\tau_i}=0,$$

where the cost is missing the price correction (a stock value) while the benefit is saving the holding cost (a flow value). Here, $f(\cdot)$ represents a probability density and $\Pr(\cdot)$ denotes a probability. The essence of our model can be summarized by the first-order condition

$$\underbrace{f\left(t_i+\tau_i=t_0+\zeta|t_i\right)\cdot\text{stock value}}_{\text{expected benefit of waiting by increasing }\tau_i}-\underbrace{\mathbf{1}\cdot\ \text{flow value}}_{\text{expected cost of waiting by increasing }\tau_i}=0$$

where the cost is sacrificing the higher profit flow (a flow value) while the benefit is saving the reputation cost (a stock value). Observe that the tradeoff between benefits and costs in our model is the opposite of that in AB's models. If we use the original setting of AB, the probability in front of the flow value would be $\Pr\left(t_i+\tau_i<t_0+\zeta|t_i\right)$, instead of 1. This means that the sign of the LHS of the first-order condition would be completely opposite in our model and in AB's models. Hence, when the first-order condition is satisfied, the optimization problem would achieve "minimization" instead of "maximization" (that is, the second-order condition would not be satisfied).

Discussion of the assumptions. We assume that a firm cannot observe other firms' price adjustments, so the information regarding t_0 is not revealed. Theoretically, prior literature has addressed why information about t_0 may not be fully revealed. For instance, Doblas-Madrid (2012), building on the framework of Abreu and Brunnermeier (2003), introduces multidimensional uncertainty to demonstrate how noise in the economy can hinder agents' ability to infer information from endogenous asset prices. Following this line of reasoning, a more complicated model could explicitly account for the fact that firms' decisions are driven by different motives, introducing multidimensional uncertainty that makes it difficult for agents to deduce information about t_0 from firms' price adjustments. In practice, collecting information on other firms' price adjustments is costly or even infeasible, given that many peer firms may be present in a large market and that a significant proportion of transactions may be conducted offline rather than online. The empirical evidence in the recent paper by Fang et al. (2024) shows that firms pay attention to only a few other firms around them.

3.3 Model Implications

In this subsection, we derive implications of our model by conducting comparative statics on the equilibrium given in Proposition 1. For clean analysis and without loss of generality, we focus on the case of $r \to 0$, under which the equilibrium equation is given by (15). We present the results

in a series of corollaries.

Corollary 2 *The delay in price adjustment, τ^*, is increasing in the magnitude of reputation cost ϱ and decreasing in the speed of declining in reputation cost $1/\beta$.*

Corollary 2 shows two results. First, the delay in price adjustment is increasing in the magnitude of reputation cost ϱ. The intuition is straightforward: firms delay price adjustment to avoid or reduce the reputation cost. Therefore, the higher the reputation cost, the stronger the incentive to wait, resulting in a longer delay. Second, if the reputation cost diminishes more rapidly (i.e., a higher $1/\beta$), firms tend to adjust prices more quickly. According to (15), $1/\beta$ affects τ^* through two opposite channels. On the one hand, a higher $1/\beta$ reduces the benefit of waiting from avoided reputation costs, as captured by $\varrho\left[1-\left(\tau^*+\kappa\eta\right)/\beta\right]$. On the other hand, a higher $1/\beta$ increases the benefit of waiting in reducing the reputation cost if it cannot be avoided, measured by ϱ/β. However, the negative channel dominates the positive one. Consequently, as $1/\beta$ increases, firms shorten the delay in their price adjustments.

Corollary 3 *Assume that the magnitude of reputation cost ϱ is proportional to π_H (i.e., $\frac{\varrho}{\pi_H}$ is a constant). The delay duration τ^* is increasing in market power α.*

It is reasonable to assume that reputation costs are positively correlated with and proportional to profit π_H. For example, the monetary loss from reputational damage for a large company like Amazon would be much greater than that for a small company. We prove that $\frac{\pi_H}{\pi_L}$ is decreasing in α, that is, for a firm with a higher market power α, the percentage profit loss from not adjusting price is smaller. Since ϱ is in proportional to π_H, it follows that $\frac{\pi_H-\pi_L}{\varrho}$ is also decreasing in α, which in turn implies that τ^* is increasing in market power α.

Corollary 3 suggests that firms with greater market power will adjust prices at a slower pace. This implication aligns with various empirical findings. For example, researches on gasoline markets by Borenstein and Shepard (2002) and Deltas (2008) indicate that firms with stronger market power tend to adjust prices more slowly. In addition, based on results of Nakamura et al. (2018), Höynck et al. (2023) demonstrate that in the United States, the frequency of price changes decreases as firms' markups increase over time.

Corollary 4 *The delay duration τ^* is decreasing in the shock size $|c'-c|$ for $c'<c$ and $c'>c$ respectively.*

Clearly, the higher the shock size $|c'-c|$, the higher the $\pi_H-\pi_L$, so it is more costly for firms to delay price adjustment. The implication of Corollary 4 is consistent with numerous empirical

findings. A rich granular dataset on price setting behavior in the food and beverage industry across multiple countries, as presented by Cavallo et al. (2023), demonstrates that larger cost shocks lead to faster price adjustments by firms. Moreover, Karadi and Reiff (2019) and Alvarez and Neumeyer (2020) highlight immediate price level responses to significant value-added tax changes in Hungary and cost shocks in Argentina, respectively. By analyzing a large cross-country panel data, Alvarez et al. (2017) find that inflation responds more quickly if the size of exchange rate shock is larger. Adding to this evidence, Bonadio et al. (2020) and Auer et al. (2021) provide empirical support for rapid currency invoicing changes following the substantial 2015 Swiss appreciation.

Corollary 5 *The delay duration τ^* is increasing in the threshold of coordination κ.*

Intuitively, a higher κ means that the threshold in coordination among firms to have no reputation cost is higher, so every firms have incentives to delay more. Concretely, according to equation (15), the coordination threshold κ affects the optimal waiting choice via three channels. First, when κ increases, the probability density of switching from a reputation status to a non-reputation status, $\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}$, becomes higher.[19] This raises the benefit of waiting. Second, when the reputation cost is avoided, its value, measured by $\varrho\left[1-\left(\tau^*+\kappa\eta\right)/\beta\right]$, decreases with higher κ. Third, as κ increases, firms are more likely to belong to the κ fractions (namely $\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}$ is higher), thus postponing price adjustment generates higher benefit. Overall, the second and third channels offset one another, leaving the first channel to dominate. Consequently, a higher κ incentivizes firms to increase waiting time τ^*.

Corollary 6 *The delay duration τ^* is decreasing in η. In particular, when $\lambda \to 0$, $\frac{d\tau^*}{d\eta} = -\frac{\pi_H-\pi_L}{\varrho/\beta}$ and thus $\eta+\tau^*$ is increasing in η if and only if $\frac{\pi_H-\pi_L}{\varrho/\beta} < 1$.*

Corollary 6 demonstrates that when information friction increases (η increases), informed firms tend to adjust price more quickly (τ^* decreases). According to equation (15), an increase in η affects the τ^* through three channels. First, the posterior probability density of switching from a reputation cost status to a non-reputation cost status, $\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}$, decreases. Second, the gain from avoiding reputation cost, $\varrho\left[1-\left(\tau^*+\kappa\eta\right)/\beta\right]$, decreases. Third, the posterior probability of paying reputation cost in equilibrium, $\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}$, decreases. Combining these three effects, the expected benefit of waiting decreases with higher η, which leads to a reduction in τ^*.

While $t_0+\tau^*$ represents the time when firms start to adjust prices, $t_0+\tau^*+\eta$ corresponds to the time when firms complete the price adjustment. Thus we investigate how $\tau^*+\eta$ responds to changes in η. Since τ^* decreases with η, an increase in η has opposing effects on $\tau^*+\eta$. For

[19] Notice that the reputation cost is avoided at time $t_i+\tau_i$ if and only if $t_0+(\tau^*+\kappa\eta)=t_i+\tau_i$, which means $t_0=t_i+\tau_i-(\tau^*+\kappa\eta)$. When κ increases, the value of t_0 decreases, and the posterior probability density that reputation cost is avoided, measured by $\phi\left(t_0|t_i\right)$, increases.

simplicity, consider the limiting case where $\lambda \to 0$. In this case, we have $\frac{d\tau^*}{d\eta} = -\frac{\pi_H - \pi_L}{\varrho/\beta}$, where ϱ/β measures the responsiveness of net benefit to the change of τ^*, and $\pi_H - \pi_L$ measures the responsiveness of net benefit to the change of η. Therefore, $\eta + \tau^*$ is increasing in η if and only if $\frac{\pi_H - \pi_L}{\varrho/\beta} < 1$.

Corollary 7 *Under the sufficient condition $\kappa < 1/2$, τ^* is decreasing in λ.*

Corollary 7 shows how the Poisson arrival rate λ affects the delay duration τ^*. When λ increases, the prior probability that shock time t_0 will arrive early becomes higher. This might lead one to expect that firms would have a stronger incentive to adjust prices sooner. While this outcome is generally true, it is not guaranteed. According to equation (15), λ affects the τ^* via two channels: the posterior probability density of switching from a reputation cost status to a non-reputation status $\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}$, and the posterior probability of paying reputation cost $\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}$. While $\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}$ is decreasing in λ, the density $\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}$ is non-monotone in λ. Overall, under the sufficient condition $\kappa < 1/2$, τ^* decreases with λ.

3.4 Conclusions

Price stickiness is the cornerstone of New Keynesian model. Among the micro foundations of price stickiness, a leading one is that firms fear antagonizing customers through price adjustments. In this paper, we provide direct evidence of customer antagonism by utilizing customers' online reviews. We find that when customers observe a firm charging a lower price than they previously paid for the same item, they feel antagonized and give low ratings to the firm, creating reputation costs for the firm. In particular, this reputation cost will be smaller if a firm adjusts its price later than other firms, which reflects a coordination motive in price adjustment.

Building on these empirical findings, we develop a model to characterize the optimal timing for firms to adjust their prices. Our analysis shows that firms may deliberately delay price changes to mitigate the high reputation costs associated with early adjustments. The model predicts both synchronized and unsynchronized price adjustments. Furthermore, it suggests that prices are stickier when a firm's market power is greater or when the size of the shock is smaller—predictions that align with empirical evidence. Our model also has other implications, namely how price stickiness is affected by the size of reputation costs, the persistence of reputation costs, and the speed of information spreading.

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Appendix

A Parameter assumptions in the model

We make three parameter assumptions in the model.

Assumption 1 *Assume* $(\pi_H - \pi_L)/\varrho < \bar{\chi}$, where

$$\bar{\chi} \equiv \frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1} + r\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1} + \frac{1/\beta}{e^{\lambda\eta}-1}\left[e^{\lambda\kappa\eta} - 1 - \lambda\kappa\eta e^{\lambda\kappa\eta} - r\left(\kappa\eta e^{\lambda\kappa\eta} - \frac{1}{\lambda}e^{\lambda\kappa\eta} + \frac{1}{\lambda}\right)\right].$$

Assumption 1 is made to ensure the equilibrium waiting time $\tau^* > 0$ (see Proposition 1). Similar to Abreu and Brunnermeier (2002), we restrict our analysis to parameter values that satisfy this condition. Absent this restriction, the equilibrium will be a corner solution, i.e., firms always adjust prices right after they become aware of that the shock has occurred.

Assumption 2 *Assume* $(\pi_H - \pi_L)/\varrho > \underline{\chi}$, where

$$\underline{\chi} \equiv \frac{r\kappa\eta}{\beta}\frac{-1}{e^{\lambda\eta}-1} + \frac{r/\beta}{e^{\lambda\eta}-1}\left[\frac{1}{\lambda}\left(e^{\lambda\kappa\eta}-1\right)\right] + \frac{1}{\beta}\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}.$$

Assumption 2 is made to ensure that the reputation cost at time $t_0+\zeta$ is positive, namely $RC(t_0+\zeta) > 0$ (see equation (14)).

Assumption 3 *Assume* $\beta^{\frac{\pi_H-\pi_L}{\varrho}} < 1$.

Assumption 3 is made to ensure that there exists a continuum of equilibrium τ^* when $\eta = 0$ and $\beta > 0$ (see Proposition 2).

There always exist parameter spaces such that Assumptions 1, 2 and 3 are simultaneously satisfied. In fact, when $r \to 0$, $\lambda \to 0$, the above three assumptions together become $\frac{\kappa}{\beta} < \frac{\pi_H-\pi_L}{\varrho} < \min\left\{\frac{1}{\eta}, \frac{1}{\beta}\right\}$.

B Proofs

Proof of Lemma 1 Firm t_i's objective function (11) can be rewritten as

$$\Psi(\tau_i) = \left[\frac{\pi_L}{r}\left[1-e^{-r\tau_i}\right] + \frac{\pi_H}{r}e^{-r\tau_i}\right] - \int_{t_i-\zeta+\tau_i}^{t_i}\phi(t_0|t_i)e^{-r\tau_i}\varrho\left[1-\frac{(t_i+\tau_i-t_0)}{\beta}\right]dt_0.$$

The first order condition gives

$$\frac{d\Psi(\tau_i)}{d\tau_i} = e^{-r\tau_i}\left\{\begin{array}{c} -(\pi_H-\pi_L) + \phi(t_i+\tau_i-\zeta|t_i)\varrho\left(1-\frac{\zeta}{\beta}\right) \\ +\int_{t_i-\zeta+\tau_i}^{t_i}\phi(t_0|t_i)\left[r\varrho\left(1-\frac{t_i+\tau_i-t_0}{\beta}\right)+\frac{\varrho}{\beta}\right]dt_0 \end{array}\right\}.$$

Defining $\frac{d\Psi(\tau_i)}{d\tau_i} \equiv e^{-r\tau_i}F(\tau_i)$, then $\frac{d\Psi(\tau_i)}{d\tau_i} = 0 \Leftrightarrow F(\tau_i) = 0$ gives equation (12) in the main text. By equation (10), $\phi(t_0|t_i) = \frac{\lambda e^{\lambda(t_i-t_0)}}{e^{\lambda\eta}-1}$ and $\phi(t_i+\tau_i-\zeta|t_i) = \frac{\lambda e^{\lambda(\zeta-\tau_i)}}{e^{\lambda\eta}-1}$, and then we have

$$\begin{aligned} F(\tau_i) &= \frac{\lambda e^{\lambda(\zeta-\tau_i)}}{e^{\lambda\eta}-1}\varrho\left(1-\frac{\zeta}{\beta}\right) + \int_{t_i-\zeta+\tau_i}^{t_i} \frac{\lambda e^{\lambda(t_i-t_0)}}{e^{\lambda\eta}-1}\left[r\varrho\left(1-\frac{t_i+\tau_i-t_0}{\beta}\right)+\frac{\varrho}{\beta}\right]dt_0 - (\pi_H-\pi_L) \\ &= \frac{\lambda e^{\lambda(\zeta-\tau_i)}}{e^{\lambda\eta}-1}\varrho\left(1-\frac{\zeta}{\beta}\right) + \int_{0}^{\zeta-\tau_i} \frac{\lambda e^{\lambda s}}{e^{\lambda\eta}-1}\left[r\varrho\left(1-\frac{\tau_i+s}{\beta}\right)+\frac{\varrho}{\beta}\right]ds - (\pi_H-\pi_L), \end{aligned}$$

where in the second line t_0 is replaced by $s = t_i - t_0$ in the integral. Also,

$$\frac{dF(\tau_i)}{d\tau_i} = (-\lambda)\frac{\lambda e^{\lambda(\zeta-\tau_i)}}{e^{\lambda\eta}-1}\varrho\left(1-\frac{\zeta}{\beta}\right) - \frac{\lambda e^{\lambda(\zeta-\tau_i)}}{e^{\lambda\eta}-1}\left[r\varrho\left(1-\frac{\tau_i+\zeta-\tau_i}{\beta}\right)+\frac{\varrho}{\beta}\right] + \int_0^{\zeta-\tau_i}\frac{\lambda e^{\lambda s}}{e^{\lambda\eta}-1}\left(-\frac{r\varrho}{\beta}\right)ds$$

and it is clear that $\frac{dF(\tau_i)}{d\tau_i} < 0$, which means that the second-order condition is satisfied. Therefore, the first-order condition $\frac{d\Psi(\tau_i)}{d\tau_i} = 0 \Leftrightarrow F(\tau_i) = 0$ gives the unique optimal waiting time τ_i^*.

Proof of Proposition 1 By equation (9), we have $\zeta = \tau^* + \kappa\eta$. With $\tau^* = \tau_i^*$, equation (12) can be written as

$$F(\tau_i)|_{\tau_i=\tau^*} = \frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\varrho\left[1-\frac{\tau^*+\kappa\eta}{\beta}\right] + \int_0^{\kappa\eta}\frac{\lambda e^{\lambda x}}{e^{\lambda\eta}-1}\left[r\varrho\left(1-\frac{x+\tau^*}{\beta}\right)+\frac{\varrho}{\beta}\right]dx - (\pi_H-\pi_L),$$

which is equation (14). It is clear that $F(\tau_i)|_{\tau_i=\tau^*}$ is monotonically decreasing in τ^*, so $F(\tau_i)|_{\tau_i=\tau^*} = 0$ pins down a unique equilibrium of τ^*. To solve τ^*, we first compute

$$\begin{array}{l} \int_0^{\kappa\eta}\frac{\lambda e^{\lambda x}}{e^{\lambda\eta}-1}\left[r\varrho\left(1-\frac{x+\tau^*}{\beta}\right)+\frac{\varrho}{\beta}\right]dx \\ = r\varrho\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\left(1-\frac{\tau^*}{\beta}\right) - \frac{r\varrho/\beta}{e^{\lambda\eta}-1}\left[\kappa\eta e^{\lambda\kappa\eta} - \frac{1}{\lambda}\left(e^{\lambda\kappa\eta}-1\right)\right] + \frac{\varrho}{\beta}\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1} \end{array}.$$

Substituting it into equation (14), $F(\tau_i)|_{\tau_i=\tau^*} = 0$ gives

$$\tau^* = \frac{\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\left[1-\kappa\eta/\beta\right] + r\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1} - \left[\frac{\pi_H-\pi_L}{\varrho} + \frac{r/\beta}{e^{\lambda\eta}-1}\left\{\kappa\eta e^{\lambda\kappa\eta} - \frac{1}{\lambda}\left(e^{\lambda\kappa\eta}-1\right)\right\} - \frac{1}{\beta}\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right]}{\left(\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1} + r\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right)/\beta}. \quad \text{(B.1)}$$

Then $\tau^* > 0$ is equivalent to

$$\frac{\pi_H-\pi_L}{\varrho} < \frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1} + r\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1} + \frac{1/\beta}{e^{\lambda\eta}-1}\left[e^{\lambda\kappa\eta}-1-\lambda\kappa\eta e^{\lambda\kappa\eta} - r\left(\kappa\eta e^{\lambda\kappa\eta} - \frac{1}{\lambda}e^{\lambda\kappa\eta} + \frac{1}{\lambda}\right)\right] \equiv \bar{\chi}$$

which is satisfied under Assumption 1. In addition, $RC\left(t_0+\zeta\right) > 0 \Leftrightarrow \tau^* < \beta - \kappa\eta$. By (B.1), $\tau^* < \beta - \kappa\eta$ can be written as

$$\frac{\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\left[1-\kappa\eta/\beta\right] + r\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1} - \left[\frac{\pi_H-\pi_L}{\varrho} + \frac{r/\beta}{e^{\lambda\eta}-1}\left\{\kappa\eta e^{\lambda\kappa\eta} - \frac{1}{\lambda}\left(e^{\lambda\kappa\eta}-1\right)\right\} - \frac{1}{\beta}\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right]}{\left(\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1} + r\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right)/\beta} < \beta - \kappa\eta,$$

and simplifying algebra yields

$$\underline{\chi} \equiv \frac{r\kappa\eta}{\beta}\frac{-1}{e^{\lambda\eta}-1} + \frac{r/\beta}{e^{\lambda\eta}-1}\left[\frac{1}{\lambda}\left(e^{\lambda\kappa\eta}-1\right)\right] + \frac{1}{\beta}\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1} < \frac{\pi_H-\pi_L}{\varrho},$$

which is satisfied under Assumption 2.

Proof of Proposition 2 When $\eta = 0$, the shock time t_0 is common knowledge. In equilibrium, we must have $\tau^* \leq \beta$. This is because at time $t_0+\beta$, the reputation cost falls to $RC(t_0+\beta) = \varrho\left(1-\beta\frac{1}{\beta}\right) = 0$.

Suppose all other firms choose $\tau^* \in (0,\beta]$, and then the reputation cost disappears at time $t_0+\tau^*$. It is obvious that no firm wants to deviate to $\tau^*+\Delta$. This is because, given other firms' choice τ^*, deviating to $\tau^*+\Delta$ only incurs profit flow loss $\pi_H-\pi_L$ but generates no benefit. Therefore, we only need to check whether a firm wants to deviate to $\tau^*-\Delta$ for all $\Delta \in (0,\tau^*]$. Suppose a firm chooses to deviate to $\tau^*-\Delta$; then the sum of benefit flow over $[t_0+\tau^*-\Delta, t_0+\tau]$ discounted back to time $t_0+\tau^*-\Delta$ is $\int_0^\Delta e^{-rs}(\pi_H-\pi_L)\,ds = \frac{1-e^{-r\Delta}}{r}(\pi_H-\pi_L)$, and the cost is $\varrho[1-(\tau^*-\Delta)/\beta]$. Thus, there is no incentive to deviate if the above benefit is smaller than the cost, namely $\frac{1-e^{-r\Delta}}{r}(\pi_H-\pi_L) < \varrho[1-(\tau^*-\Delta)/\beta]$ or

$$\tau^* < f(\Delta) \quad \text{for any } \Delta \in (0,\tau^*], \tag{B.2}$$

where $f(\Delta) \equiv \left(1-\frac{1-e^{-r\Delta}}{r}\frac{\pi_H-\pi_L}{\varrho}\right)\beta + \Delta$.

Under assumption 3 (i.e., $\beta\frac{\pi_H-\pi_L}{\varrho} < 1$), $f'(\Delta) > 0$; that is, $f(\Delta)$ is monotonically increasing in $\Delta \in (0,\tau^*]$ for any τ^*, and thus $f(\Delta) > f(0) = \beta$ for any $\Delta \in (0,\tau^*]$. Therefore, for any $\tau^* \leq \beta$, condition (B.2) holds.

Proof of Proposition 3 When $\beta = 0$, by (8), there is no reputation cost associated with price adjustment. This means a positive delay in price adjustment only leads to cost of cash flow $\pi_H-\pi_L$, while generating no benefit. Thus, all firms will choose $\tau^* = 0$.

Proof of Corollary 1 The proof of Corollary 1 follows the same logic as the proof of Proposition 3.

Proof of Corollary 2 First, it is obvious that the left-hand side of equation (15) is increasing in ϱ. Thus, when ϱ increases, the optimal τ^* increases.

Second, using equation (15), the FOC with respect to $1/\beta$ gives $\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\varrho\left[(\tau^*+\kappa\eta)+\frac{1}{\beta}\frac{d\tau^*}{d(1/\beta)}\right] = \frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\varrho$, which further simplifies to:

$$\frac{d\tau^*}{d(1/\beta)} = \left[\frac{e^{\lambda\kappa\eta}-1}{\lambda e^{\lambda\kappa\eta}} - (\tau^*+\kappa\eta)\right]\beta$$

Define $f(\lambda) \equiv \frac{e^{\lambda\kappa\eta}-1}{\lambda e^{\lambda\kappa\eta}} = \frac{1-e^{-\lambda\kappa\eta}}{\lambda}$, then $\frac{d\tau^*}{d(1/\beta)} < 0$ if and only if $f(\lambda) < \tau^*+\kappa\eta$. To prove $f(\lambda) < \tau^*+\kappa\eta$, we first prove $\frac{df(\lambda)}{d\lambda} = \frac{\lambda\kappa\eta e^{-\lambda\kappa\eta}-1+e^{-\lambda\kappa\eta}}{\lambda^2} < 0$. Define $g(x) \equiv xe^{-x}-1+e^{-x}$ for $x > 0$, then $\frac{dg(x)}{dx} = e^{-x}-x^2e^{-x}-e^{-x} < 0$. Additionally, $g(0) = 0$, so $g(x) < 0$ for $x > 0$,

which means $g(\lambda\kappa\eta) < 0$ for $\lambda > 0$. Therefore, $\frac{df(\lambda)}{d\lambda} = \frac{g(\lambda\kappa\eta)}{\lambda^2} < 0$ for $\lambda > 0$. Consequently, $f(\lambda) < f(0) = \kappa\eta \leq \tau^* + \kappa\eta$. This means $\frac{d\tau^*}{d(1/\beta)} < 0$.

Proof of Corollary 3 To prove Corollary 3, we first prove $\frac{\pi_H}{\pi_L}$ is decreasing in α. Suppose cost c changes from c_0 to $c_1 = c_0 + \Delta c$. Define

$$q(\alpha) \equiv \frac{\pi_H}{\pi_L} = \frac{\left(\frac{c_1}{1-\alpha} - c_1\right)\left(\frac{c_1}{1-\alpha}\right)^{-\frac{1}{\alpha}}}{\left(\frac{c_0}{1-\alpha} - c_1\right)\left(\frac{c_0}{1-\alpha}\right)^{-\frac{1}{\alpha}}} = \frac{(c_1 - (1-\alpha)c_1)}{(c_0 - (1-\alpha)c_1)}\left(\frac{c_1}{c_0}\right)^{-\frac{1}{\alpha}},$$

then we we prove $\frac{dq(\alpha)}{d\alpha} < 0$. We need to consider two cases.

Case (i): $\frac{c_0}{1-\alpha} - c_1 > 0$. In this case, we have $q(\alpha) > 0$. Thus $\frac{dq(\alpha)}{d\alpha} < 0 \Leftrightarrow \frac{d\log[q(\alpha)]}{d\alpha} < 0$, with

$$\frac{d\log[q(\alpha)]}{d\alpha} = \frac{-(c_1 - c_0)c_1}{(c_1 - (1-\alpha)c_1)(c_0 - (1-\alpha)c_1)} + \frac{1}{\alpha^2}\log\left(\frac{c_1}{c_0}\right)$$

Define $g(\Delta c) \equiv \frac{d\log[q(\alpha)]}{d\alpha}$, then $g(\Delta c) = \frac{-\Delta c \cdot c_1}{(c_1-(1-\alpha)c_1)(c_0-(1-\alpha)c_1)} + \frac{1}{\alpha^2}\log\left(1 + \frac{\Delta c}{c_0}\right)$, and $g(0) = 0$. In addition,

$$g'(\Delta c) = \frac{-c_1}{(c_1 - (1-\alpha)c_1)(c_0 - (1-\alpha)c_1)} + \frac{1}{\alpha^2}\frac{1/c_0}{1 + \Delta c/c_0} = \frac{1}{c_1}\left[\frac{-1}{\alpha\left(\frac{c_0}{c_1} - (1-\alpha)\right)} + \frac{1}{\alpha^2}\right]$$

Thus, $g'(\Delta c) > 0$ if $c_1 < c_0$ and $g'(\Delta c) < 0$ if $c_1 > c_0$. Thus, $g(\Delta c)$ is largest at $\Delta c = 0$, which means $g(\Delta c) < 0$ always hold for $\Delta c \neq 0$. Thus $\frac{d\log[q(\alpha)]}{d\alpha} < 0$.

Case (ii): $\frac{c_0}{1-\alpha} - c_1 < 0$. In this case, $(1-\alpha)c_1 - c_0 > 0$ and $q(\alpha) < 0$. Then $\frac{dq(\alpha)}{d\alpha} < 0 \Leftrightarrow \frac{d[-q(\alpha)]}{d\alpha} > 0 \Leftrightarrow \frac{d\log[-q(\alpha)]}{d\alpha} > 0$. We only need to show

$$\frac{d\log[-q(\alpha)]}{d\alpha} = \frac{c_1}{c_1 - (1-\alpha)c_1} + \frac{c_1}{(1-\alpha)c_1 - c_0} + \frac{1}{\alpha^2}\log\left(\frac{c_1}{c_0}\right) > 0$$

This condition holds by using $\alpha \in (0,1)$ and $(1-\alpha)c_1 - c_0 > 0$.

Combining Case (i) and Case (ii), we establish that $\frac{\pi_H}{\pi_L}$ is decreasing in α. Since ϱ is proportional to π_H, $\frac{\pi_H - \pi_L}{\varrho}$ is also decreasing in α. Notice the equilibrium conditioin (15) can be written as

$$\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta} - 1}\left[1 - \frac{\tau^* + \kappa\eta}{\beta}\right] + \frac{e^{\lambda\kappa\eta} - 1}{e^{\lambda\eta} - 1}\frac{1}{\beta} = \frac{\pi_H - \pi_L}{\varrho}$$

Since $\frac{\pi_H - \pi_L}{\varrho}$ is decreasing in α, it implies that τ^* is increasing in α.

Proof of Corollary 4 Given the initial c, define $f(c') \equiv \pi_H - \pi_L = \left(\frac{c'}{1-\alpha} - c'\right)\left(\frac{c'}{1-\alpha}\right)^{-\frac{1}{\alpha}} - \left(\frac{c}{1-\alpha} - c'\right)\left(\frac{c}{1-\alpha}\right)^{-\frac{1}{\alpha}}$. FOC with respect to c' gives $\frac{df(c')}{dc'} = -\left(\frac{c'}{1-\alpha}\right)^{-\frac{1}{\alpha}} + \left(\frac{c}{1-\alpha}\right)^{-\frac{1}{\alpha}}$. Thus, $\frac{df(c')}{dc'} >$

0 if $c' > c$ and $\frac{df(c')}{dc'} < 0$ if $c' < c$. This implies $f(c') = 0$ for $c' = c$ is the minimum. Therefore, $f(c') = \pi_H - \pi_L$ is increasing in $|c' - c|$ for $c' < c$ and $c' > c$ respectively.

Proof of Corollary 5 Denote by LHS the left-hand side of equilibrium conditioin (15), then

$$\frac{\partial LHS}{\partial \kappa} = \frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\lambda\eta\varrho\left[1-\frac{\tau^*+\kappa\eta}{\beta}\right]+\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\varrho\left(-\frac{\eta}{\beta}\right)+\frac{e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\frac{\lambda\eta\varrho}{\beta} = \frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\lambda\eta\varrho\left[1-\frac{\tau^*+\kappa\eta}{\beta}\right]$$

It follows that $\frac{\partial LHS}{\partial \kappa} > 0$ if and only if $1-(\tau^*+\kappa\eta)/\beta > 0$. The condition $1-(\tau^*+\kappa\eta)/\beta > 0$ means the reputation cost has not decreases to zero by the time $t_0+\zeta$, which holds under Assumption 2. Combining $\frac{\partial LHS}{\partial \kappa} > 0$ and $\frac{\partial LHS}{\partial \tau^*} < 0$, it is clear that τ^* is increasing in κ.

Proof of Corollary 6 Consider the first term in the LHS of the equilibrium conditioin (15), we have $\frac{\partial\left[\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\right]}{\partial\eta} = \frac{\lambda^2\kappa e^{\lambda\kappa\eta}\left(e^{\lambda\eta}-1\right)-\lambda^2 e^{\lambda\kappa\eta}e^{\lambda\eta}}{\left(e^{\lambda\eta}-1\right)^2} = \frac{\lambda^2 e^{\lambda\kappa\eta}e^{\lambda\eta}\left(\kappa-\kappa e^{-\lambda\eta}-1\right)}{\left(e^{\lambda\eta}-1\right)^2} < 0$ and $\frac{\partial[(\tau^*+\kappa\eta)/\beta]}{\partial\eta} = \frac{\kappa}{\beta} > 0$. For the second term in the LHS of (15), we have

$$\frac{\partial\left[\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right]}{\partial\eta} = \frac{\lambda\kappa e^{\lambda\kappa\eta}\left(e^{\lambda\eta}-1\right)-\lambda\left(e^{\lambda\kappa\eta}-1\right)e^{\lambda\eta}}{\left(e^{\lambda\eta}-1\right)^2} = \frac{\kappa-\kappa e^{-\lambda\eta}-1+e^{-\lambda\kappa\eta}}{\left(e^{\lambda\eta}-1\right)^2}\lambda e^{\lambda\eta}e^{\lambda\kappa\eta}$$

Define $g(\eta) \equiv \kappa-\kappa e^{-\lambda\eta}-1+e^{-\lambda\kappa\eta}$, then $g(0) = 0$. In addition, $g'(\eta) = \lambda\kappa e^{-\lambda\eta}-\lambda\kappa e^{-\lambda\kappa\eta} < 0$. Thus $g(\eta) < 0$ for $\eta > 0$, which implies $\frac{\partial\left(e^{\lambda\kappa\eta}-1\right)/\left(e^{\lambda\eta}-1\right)}{\partial\eta} = \frac{g(\eta)}{\left(e^{\lambda\eta}-1\right)^2}\lambda e^{\lambda\eta}e^{\lambda\kappa\eta} < 0$. Combining $\frac{\partial\left[\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\right]}{\partial\eta} < 0$, $\frac{\partial[(\tau^*+\kappa\eta)/\beta]}{\partial\eta} > 0$, and $\frac{\partial\left(e^{\lambda\kappa\eta}-1\right)/\left(e^{\lambda\eta}-1\right)}{\partial\eta} < 0$, it is clear that the LHS of the equilibrium conditioin (15) is decreasing in η. Since it is also decreasing τ^*, thus τ^* is decreasing in η.

For the extreme case where $\lambda \to 0$, (15) can be written as

$$\frac{1}{\eta}\varrho\left[1-(\tau^*+\kappa\eta)/\beta\right]+\frac{\kappa\varrho}{\beta}-(\pi_H-\pi_L) = 0. \tag{B.3}$$

FOC over η gives $-\frac{1}{\eta^2}\varrho\left[1-(\tau^*+\kappa\eta)/\beta\right] = \frac{1}{\eta\beta}\varrho\left(\frac{d\tau^*}{d\eta}+\kappa\right)$. Rearrange terms we have $\frac{\varrho}{\beta}\left(\frac{d\tau^*}{d\eta}+\kappa\right) = -\frac{1}{\eta}\varrho\left[1-(\tau^*+\kappa\eta)/\beta\right] = \frac{\kappa\varrho}{\beta}-(\pi_H-\pi_L)$, where we use (B.3) in the second equation. This gives $\frac{d\tau^*}{d\eta} = -\frac{\pi_H-\pi_L}{\varrho/\beta}$.

Proof of Corollary 7 Consider the first term in the LHS of (15), we have

$$\frac{\partial\left(\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\right)}{\partial\lambda} = \frac{\partial\left(\frac{\lambda}{e^{\lambda\eta(1-\kappa)}-e^{-\lambda\kappa\eta}}\right)}{\partial\lambda} = \frac{\left[e^{\lambda\eta(1-\kappa)}-e^{-\lambda\kappa\eta}\right]-\lambda\left[\eta(1-\kappa)e^{\lambda\eta(1-\kappa)}+\kappa\eta e^{-\lambda\kappa\eta}\right]}{\left[e^{\lambda\eta(1-\kappa)}-e^{-\lambda\kappa\eta}\right]^2}$$

Define $g(\lambda) \equiv \left[e^{\lambda\eta(1-\kappa)}-e^{-\lambda\kappa\eta}\right]-\lambda\left[\eta(1-\kappa)e^{\lambda\eta(1-\kappa)}+\kappa\eta e^{-\lambda\kappa\eta}\right]$, then $g'(\lambda) = -\lambda\left[(\eta(1-\kappa))^2 e^{\lambda\eta(1-\kappa)}-(\kappa\eta)^2\right.$
If $1-\kappa > \kappa$, $g'(\lambda)$ is always negative. Since $g(0) = 0$, we have $g(\lambda) < 0$ if $\kappa < 1/2$, which means

$\frac{\partial\left(\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\right)}{\partial\lambda} < 0$ if $\kappa < 1/2$. Next, consider the second term in the LHS of (15), we have

$$\frac{\partial\left(\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right)}{\partial\lambda} = \frac{\kappa\eta e^{\lambda\kappa\eta}\left(e^{\lambda\eta}-1\right)-\eta\left(e^{\lambda\kappa\eta}-1\right)e^{\lambda\eta}}{\left[e^{\lambda\eta}-1\right]^2} = \frac{\kappa\eta\left(1-e^{-\lambda\eta}\right)-\eta\left(1-e^{-\lambda\kappa\eta}\right)}{\left[e^{\lambda\eta}-1\right]^2}e^{\lambda\eta}e^{\lambda\kappa\eta}$$

Define $g(\lambda) \equiv \kappa\eta\left(1-e^{-\lambda\eta}\right)-\eta\left(1-e^{-\lambda\kappa\eta}\right)$, then $g'(\lambda) = \kappa\eta^2 e^{-\lambda\eta}-\kappa\eta^2 e^{-\lambda\kappa\eta} = \kappa\eta^2 e^{-\lambda\eta}\left(1-e^{\lambda(1-\kappa)\eta}\right) < 0$. Using $g(0) = 0$, we have $g(\lambda) < 0$, thus $\frac{\partial\left(\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right)}{\partial\lambda} < 0$. In summary, if $\kappa < 1/2$, we have $\frac{\partial\left(\frac{\lambda e^{\lambda\kappa\eta}}{e^{\lambda\eta}-1}\right)}{\partial\lambda} < 0$ and $\frac{\partial\left(\frac{e^{\lambda\kappa\eta}-1}{e^{\lambda\eta}-1}\right)}{\partial\lambda} < 0$. This means the LHS of equilibrium condition (15) is decreasing in λ, thus τ^* is decreasing in λ.

C Additional Empirical Results

C.1 Robustness Checks: Existence of Reputation Cost

We provide a robustness check with respect to Finding 1. In the main text, the positive coefficient β in regression (2) shows that stores suffer higher reputation costs during price reduction periods. Here we will check it by a direct t-test. Specifically, we separate all samples into two groups - the group of price reduction periods and the group of other periods. We include all price reduction periods shown in Figure 1.[20] Therefore, the t-test between two groups can provide a direct comparison of reputation costs.

Figure 6 illustrates the distribution of stores. In the box plot, the left group is the subsample in price reduction periods and the right group is the subsample in other periods. The mean values of reputation costs for the "price redcution periods" and "other periods" groups are 0.203 and 0.158, respectively; while the standard deviations of those are 0.252 and 0.248, respectively. The difference in mean values of reputation costs amounts to 0.045, and the associated t-statistic is 3.21. This indicates that the divergence between the two groups is statistically significant at the one percent level.

[20] The shadow part in Figure 1 shows all average-price-decline periods, including January 01, 2019 to July 06, 2019, July 23, 2019 to August 25, 2019, October 15, 2019 to December 08, 2019 and March 23, 2020 to December 22, 2020. Inversely, the non-shadow part in Figure 1 presents other periods.

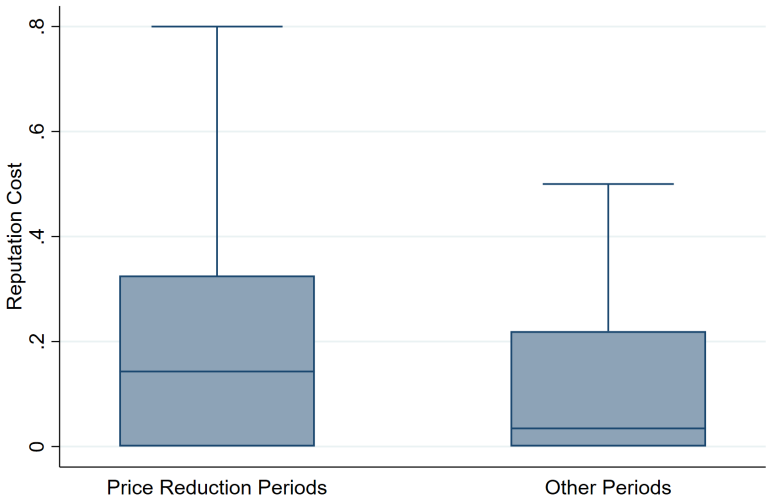


Figure 6: Comparison of Reputation Costs

C.2 Alternative Measures of Sticky Stores

In this section, we introduce two alternative measures of sticky stores and demonstrate that our primary conclusions remain robust.

Alternative Measure 1

In the main text, a store is classified as sticky if it takes longer to achieve a 5% price reduction relative to its initial price. For robustness, we redefine sticky stores based on the time required to achieve 10%, 15%, and 20% price reductions. Following a similar methodology, we arrange the number of days it takes for all stores to reach these thresholds in ascending order and group them into quantiles, as shown in Table A1.

Table A1: Number of Days to Complete a n% Price Reduction

Quantiles	10% Reduction	15% Reduction	20% Reduction
20%	11	19	31
40%	26	38	53
median	35	53	69
60%	51	72	99
80%	105	162	192

The regression analysis supporting Finding 2 is presented in Table A2. Consistent with the conclusions in the main text, stores that reduce prices more quickly incur significantly higher reputation costs compared to those that adjust prices more slowly.

Table A2: Price Reduction Speed and Reputation Cost

	10% Reduction	15% Reduction	20% Reduction
non-sticky	4.07***	4.77***	4.01***
	(1.09)	(1.07)	(1.09)
Time FE	Y	Y	Y
Controls	Y	Y	Y
Cluster	Y	Y	Y
Observations	1589	1589	1589
R^2	0.14	0.14	0.14

Note: This table reports the results of regressing reputation costs on the non-sticky dummy variable. Statistical significance levels of 1 percent, 5 percent, and 10 percent are indicated by ***, ** and *, respectively.

Alternative Measure 2

We propose another method to distinguish between sticky and non-sticky stores, focusing on the price reduction cycle from March 23, 2020, to December 22, 2020.

First, we compute the total price reduction for each store over this period, referred to as TPR (Total Price Reduction). Next, a store is classified as sticky if it takes longer to reduce its price by $n\%$ of its TPR, where we choose n =15, 20, 25 and 50. This alternative measurement accounts for some store heterogeneity, such as differences in initial prices before the price reduction cycle. While the main text's definition may not fully capture these nuances, our alternative approach helps address these limitations, serving as an additional robustness check. Table A3 shows the quantiles for the number of days required to reach $n\%$-TPR.

Table A3: **Number of Days to Complete a n%-TPR**

Quantiles	15%-TPR	20%-TPR	25%-TPR	50%-TPR
20%	7	8	11	31
40%	15	18	21	46
median	20	24	29	54
60%	29	33	38	65
80%	65	66	70	101

Table A4 presents the regression analysis supporting Finding 2. On average, non-sticky stores face a significant increase in reputation costs, ranging from 4% to 5%, during periods of price reductions.

Table A4: Price Reduction Speed and Reputation Cost

	15%-TPR	20%-TPR	25%-TPR	50%-TPR
non-sticky	4.55***	4.83***	5.25***	4.15***
	(1.10)	(1.09)	(1.06)	(1.12)
Time FE	Y	Y	Y	Y
Controls	Y	Y	Y	Y
Cluster	Y	Y	Y	Y
Observations	1589	1589	1589	1589
R^2	0.14	0.14	0.14	0.14

Note: Table A4 reports the results of regressing reputation costs on the non-sticky dummy variable under standard fixed effect models. All results are adjusted by cluster of stores. Statistical significance levels of 1 percent, 5 percent, and 10 percent are indicated by "***", "**" and "*", respectively.